

Probing Hot and Dense Matter with Charm and Bottom Measurements with PHENIX VTX Tracker

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Abstract

We present the first measurements of the nuclear modification factor (R_{AA}) for flavor-separated b , c -quark electrons in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The newly installed Silicon Vertex Tracker is used to measure the distance of closest approach distributions of electrons at midrapidity ($|\eta| < 0.35$) over the transverse momentum range $1 < p_T^e < 5$ GeV/ c . From this, the relative fraction of bottom (b) and charm (c) quarks is determined in both the $p+p$ and Au+Au collision systems, which form the basis of the measured R_{AA} . In $p+p$, we observe that a FONLL perturbative QCD calculation of $b \rightarrow e/(c \rightarrow e + b \rightarrow e)$ ratio is in good agreement with the data. In Au+Au, the data imply a large suppression of $b \rightarrow e$ or a large modification of B meson p_T distributions, which implies very interesting physics of B mesons in Au+Au collisions.

1. Physics Motivation

In relativistic heavy ion collisions at RHIC, heavy quarks (charm, c , or bottom, b) are expected to be primarily created from initial hard parton scatterings [1] and carry information from the system at an early stage. The interaction between heavy quarks and the medium is sensitive to the medium dynamics, therefore heavy quarks are suggested as an ideal probe to quantify the properties of the strongly interacting QCD matter. Heavy quark production has been studied by the PHENIX experiment via the measurement of electrons from semi-leptonic decays of hadrons carrying charm (noted c) or bottom (noted b) quarks. A large suppression and strong elliptic flow of single electron heavy flavor has been observed in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV [2]. This suppression is found to be similar to that of light mesons which implies a substantial energy loss of fast heavy quarks while traversing the medium. The strong flow implies that the same heavy quarks are in fact sensitive to the pressure gradients driving hydrodynamic flow – giving new insight into the strongly coupled nature of the QGP fluid at these temperatures. For these earlier results, PHENIX was not able to distinguish electrons from c and b quarks. In order to understand medium effects in more detail, it became imperative to directly measure the nuclear modification, and the flow, of c and b separately. Based on this motivation, in December 2010, the PHENIX Collaboration opened a new era for measuring heavy flavor at RHIC by installing a new detector called the Silicon Vertex Tracker (VTX).

¹ A list of members of the PHENIX Collaboration and acknowledgments can be found at the end of this issue.

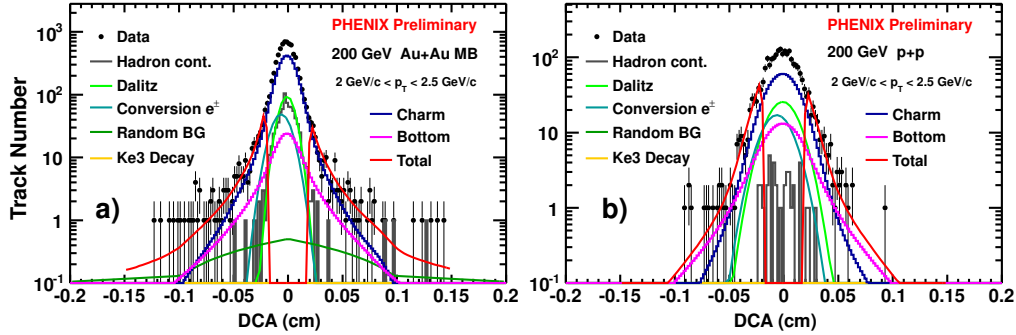


Figure 1: DCA distribution of $2 < p_T^e < 2.5$ GeV/c electrons measured at $\sqrt{s_{NN}} = 200$ GeV in (a) minimum-bias Au+Au and (b) $p+p$ collisions. The curves represent the decomposed contribution of charm, bottom, photonic background, and other components. The total curve is shown for the fit range used to extract the b and c ratio (see text for details).

The new VTX detector benefits three areas for PHENIX heavy flavor measurements. First, by selecting electrons with a distance of closest approach (DCA) to the primary vertex larger than $\sim 100 \mu\text{m}$, the photonic electron background is suppressed by orders of magnitude. This suppression results in a clean and robust measurement of heavy flavor production in the single electron channel. Secondly, as the lifetime of mesons containing bottom is significantly longer than those containing charm, the detailed DCA distribution from the VTX allows to disentangle charm from bottom production over a broad p_T range. Thirdly, a DCA cut to remove hadrons reduces the combinatorial background of $K\pi$ such that a direct measurement of D mesons through this decay channel will be possible. In this paper, we present the first PHENIX measurements using the VTX to measure the DCA of electrons at midrapidity. From this, the yield ratio of single electrons from bottom to those from all heavy flavor, as well as the nuclear modification factor of charm and bottom separately, are presented using minimum-bias (MB) Au+Au and $p+p$ collisions at $\sqrt{s_{NN}} = 200$ GeV obtained in the 2011 and 2012 RHIC runs.

2. PHENIX Central Detectors

Electron identification in PHENIX utilizes the two central-arm detectors [3]. Until 2010, a combination of tracker and electromagnetic calorimeter systems allowed for electron, photon, and hadron measurements over the range $|\eta| < 0.35$ and $\Delta\phi = \pi/2$ in azimuth. In 2010, the central detector was upgraded to include the VTX ready for Run 2011. Starting from the beam line, the complete detector now comprises the new VTX, which is followed by another tracker system made of two sets of drift chambers and a pad chamber (PC1). Outside of the PC1 detector is a Ring Image Cherenkov detector (RICH), which provides electron/hadron separation from p_T of a few hundred MeV/c to about 5 GeV/c. The last layer of the spectrometer is an electromagnetic calorimeter which is used for photon measurements and electron/hadron separation.

The VTX was commissioned in Run 2011 using $p+p$ collision data at $\sqrt{s} = 500$ GeV. Commissioning was followed by a period of data collection, which forms the basis of the physics measurements presented here, in 2011 (for Au+Au) and 2012 (for $p+p$) RHIC runs. The VTX detector consists of four layers of barrel detectors which cover $|\eta| < 1.2$ and almost 2π in azimuth. The inner two barrels consist of a silicon pixel device with $50 \times 425 \mu\text{m}$ pixel size. The outer

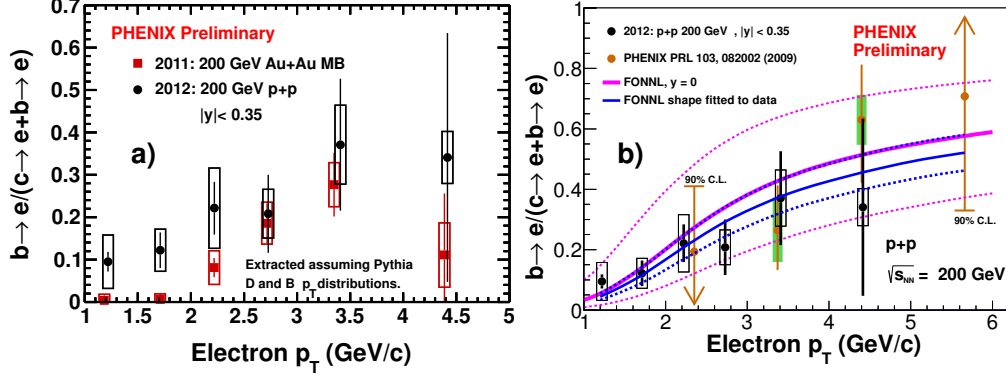


Figure 2: (a) Fraction of $b \rightarrow e$ to the total $(c \rightarrow e + b \rightarrow e)$ as a function of electron p_T^e for minimum-bias Au+Au and $p+p$ at $\sqrt{s_{NN}} = 200$ GeV. Panel (a) shows a comparison between the two systems. These extracted fractions were obtained assuming PYTHIA D and B p_T distributions. Au+Au data include no uncertainties from modified p_T spectra. Panel (b) shows a comparison between $p+p$ and a FONLL [6].

barrels consist of silicon strip detectors with stereoscopic strips of $80 \mu\text{m} \times 3 \text{ cm}$, these devices achieve an effective pixel size of $80 \times 1000 \mu\text{m}$. Details of the VTX can be found in Ref. [4].

3. Measurement of the Nuclear Modification Factor for Charm and Bottom

The first step in measuring R_{AA} for c and b is to determine the distance of closest approach (DCA) of the candidate electrons to the primary collision vertex. As electrons from D and B mesons decays do not originate at the primary collision vertex, they have a large DCA. For example, the decay-lengths of D^0 and B^0 are 123 and $457 \mu\text{m}$ respectively. This differentiation using the DCA is only made possible by the tracking through the VTX. In the present measurements, a precise primary collision vertex — $0 - 5\%$ central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV has a resolution ($\sigma_x, \sigma_y, \sigma_z$) of $(54 \pm 2, 37 \pm 2, 68 \pm 2) \mu\text{m}$ — is determined by stand-alone-tracking using the VTX. These resolutions will be improved by future fine adjustments to the alignment of the detector.

Once candidate electrons are determined from the original PHENIX central arm components, they are matching to a set of clusters in the VTX. The momentum of the track is measured by the Drift Chamber. Electron identification is done by RICH and energy momentum matching. The VTX-portion of the reconstructed candidate is used to determine the DCA to the collision vertex allows the statistical extraction of flavor identification. Figure 1 shows the raw DCA distributions of electrons measured at $\sqrt{s_{NN}} = 200$ GeV for both minimum bias Au+Au (panel a) and $p+p$ (b) collisions in the range $2 < p_T^e < 2.5$ GeV/c. The DCA resolutions are estimated to be 70 and $138 \mu\text{m}$, in Au+Au and $p+p$ respectively. In the present work, the DCA resolution for $p+p$ was determined relative to the beam center, rather than the collision vertex as used with Au+Au collisions, which avoids auto-correlations due to the low multiplicity.

The curves presented in Fig. 1 represent the decomposition of the DCA distributions from all expected signal and background contributions. For each p_T^e bin, we first define a DCA fit function, which has contributions from photonic, charm, bottom, K_{e3} , and a constant-BG, from which the component yields are obtained. The amount of hadron contamination was determined using

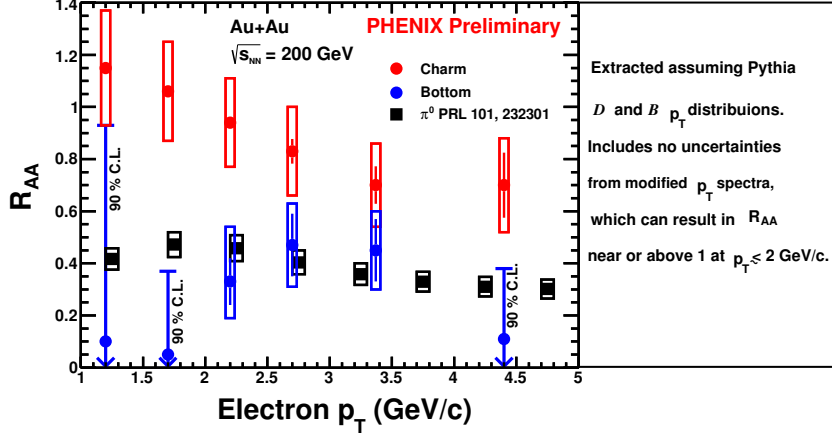


Figure 3: R_{AA} of electrons from charm and bottom decays in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The results are compared to published PHENIX π^0 [7].

the RICH swap method – a standard procedure of PHENIX electron analyses [5]. The DCA distributions of the photonic components (Dalitz, photon conversion) are Gaussian distributions, which was confirmed with a full GEANT simulation of the PHENIX detector. We additionally studied the effect of high multiplicities (expected in Au+Au collisions) on the DCA distribution by embedding simulated electrons and pions in real Au+Au data. This study indicated that the effect on the DCA due to the high occupancy is small and justifies the use of a pure Gaussian distribution as the shape of the photonic component. The DCA distribution shape of the c , b , and K_{e3} decay components were determined by simulation. The c and b distribution shapes were generated using PYTHIA ($b \rightarrow e$ and $c \rightarrow e$) decays convoluted with the DCA resolution of the VTX detector. This was cross checked using a full simulation. The K_{e3} background normalization is determined from the number of charged hadrons in the same p_T bin, the measured K/h ratio, the branching ratios of K_{e3} , and a simulation of K_{e3} decays. There are additional backgrounds at large DCA in the data that are caused by conversion electrons in the outer VTX layers. In low multiplicity events, these outer layer conversions are removed by the requirement of hits in the first two barrels B0 and B1 of the VTX. However, in Au+Au collisions, some of these conversions are confirmed by random hits in the VTX. Since they are caused by random matching with unrelated hits in the VTX, their DCA distribution is broad, almost flat. This random background was evaluated using a sideband method which showed that the distribution is consistent with flat DCA along z in the region $0.75 < |DCA_Z| < 1.0$ mm.

The total number of inclusive electrons, N_e^{inc} , are obtained after subtracting the backgrounds (hadron contamination, K_{e3} , and constant BG) from the total number electrons in the DCA distribution. The number of b and c are obtained using $N^b = N_e^{inc} \times R_{HQ} \times F^b$ and $N^c = N_e^{inc} \times R_{HQ} \times (1 - F^b)$, respectively. Here F^b is the fraction of b in heavy flavor electrons, $F^b = b \rightarrow e / (c \rightarrow e + b \rightarrow e)$, which is the only unknown parameter. The R_{HQ} is defined as $R_{HQ} = N_e^{HF} / N_e^{inc}$ which was estimated by two methods: one based on 2004 data of photonic/non-photonic ratio and the other based on measured conversion tagging probability using 2011 data.

Figure 2a shows the resulting bottom fraction, $F^b = b \rightarrow e / (c \rightarrow e + b \rightarrow e)$, as a function of electron p_T^e measured in MB Au+Au and for $p+p$ collisions at $\sqrt{s_{NN}} = 200$ GeV. The ratio in $p+p$ collisions is compared to a fixed-order-plus-next-to-leading-log (FONLL) perturbative QCD

calculation (pink curves) [6] as shown in Fig. 2b. We observe that FONLL is in good agreement with current and previous published [5] PHENIX results. Owing to the large uncertainties in the $p+p$ data the FONLL calculation shape is varied to fit all experimental data points of F^b (FONLL blue solid curve). The blue dashed curves represent 1σ uncertainties from the FONLL shape fit procedure. The F^b ratio is used to form R_{AA} for c and b using Eqn. 1:

$$R_{AA}^{b \rightarrow e} = R_{AA}^{b+c \rightarrow e} \frac{F_{AA}^b}{F_{ppFit}^b} \quad \text{and} \quad R_{AA}^{c \rightarrow e} = R_{AA}^{b+c \rightarrow e} \frac{1 - F_{AA}^b}{1 - F_{ppFit}^b} \quad (1)$$

where $R_{AA}^{b+c \rightarrow e}$ is the nuclear modification factor for single electrons heavy flavor measured by PHENIX [8]. We observe that the nuclear modification of c is less than that for π^0 s ($R_{AA}^{c \rightarrow e} > R_{AA}^{\pi^0}$), as shown in Fig. 3.

The bottom/charm separation results, shown in Figs 2 and 3, are extracted assuming PYTHIA D and B p_T distributions. These results demonstrate that the Au+Au data are inconsistent with these input assumptions unless there is also a large suppression of electrons from bottom across the measured p_T^e range. This large suppression implies a large change in the parent hadron p_T distributions, which results in changes in the electron DCA distributions. This causes an additional set of uncertainties in $R_{AA}^{b \rightarrow e}$ which are not included in Figure 3. Because the charm fraction dominates at low p_T^e , the $R_{AA}^{c \rightarrow e}$ is less affected. We are actively working on evaluation of these uncertainties. These results imply that either a large suppression of $b \rightarrow e$ or a large modification of B meson p_T distributions, which implies very interesting physics of B mesons in Au+Au collisions.

4. Summary

The DCA distributions of single electrons have been measured by the VTX detector in $p+p$ and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. By selecting electrons with a DCA to the primary vertex larger than $100 \mu\text{m}$, the photonic electron background was suppressed by orders of magnitude. This suppression results in a clean and robust measurement of heavy flavor production in the single electron channel. From this, the relative fraction of b and c quarks is determined. In $p+p$, the FONLL perturbative QCD calculation of $b \rightarrow e/(c \rightarrow e + b \rightarrow e)$ ratio is in good agreement with the data. This allows us to measure R_{AA} for single electrons from D and B decays. We observe a higher R_{AA} , i.e. less suppression, for D mesons compared that observed for π^0 s. While for B , the data imply a large suppression of $b \rightarrow e$ or a large modification of B meson p_T distributions. It should be noted that the bottom/charm separation results are extracted assuming PYTHIA D and B p_T distribution. This leads to additional uncertainties in R_{AA} which are not included in the present results; PHENIX Collaboration is actively working on evaluation of the uncertainties.

References

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